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Pre- and post-emergence herbicide sequences for management of multiple herbicide-resistant littleseed canary grass in wheat

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ABSTRACT

Littleseed canary grass (*Phalaris minor*) is the ubiquitous and pernicious grass weed of wheat in rice-wheat cropping system in north-western Indo- Gangetic plains of India. A field experiment was conducted during *Rabi* 2014-15 and 2015-16 in a farmers field infested with *P. minor* having history of poor control with acetyl-CoA-carboxylase inhibitors in village Nangla, district Fatehabad, Haryana, India with an objective to compare pre-emergence only, post-emergence only and pre-emergence followed by post-emergence herbicide treatments for control of *P. minor* in wheat. The sequential application of pre-emergence pendimethalin 1.5 kg/ha *fb* post-emergence pinoxaden + metsulfuron 64 g/ha and pre-emergence pendimethalin 1.5 kg/ha *fb* post-emergence mesosulfuron + iodosulfuron 14.4 g/ha provided 88-93% control of *P. minor* compared to alone pre- and post-emergence herbicide treatments. Grain yield of wheat increased significantly by 69-78% with pre-emergence pendimethalin 1.5 kg/ha *fb* post-emergence pinoxaden + metsulfuron 64 g/ha or pre-emergence pendimethalin 1.5 kg/ha *fb* post-emergence mesosulfuron + iodosulfuron 14.4 g/ha due to significant increase in yield attributes. Alone pre- or post-emergence herbicides provided ineffective control of *P. minor* (44-66%) and recorded lower grain yield. It was concluded that herbicide sequences having both pre- and post-emergence herbicides would be better option as compared to their alone applications in order to manage resistant populations of *P. minor* in wheat.

INTRODUCTION

Littleseed canary grass (*Phalaris minor* Retz.) is a native weed of Mediterranean region, and is widely distributed in many parts of the world covering all the continents except the Polar Regions (Singh *et al.* 1999). In India, it is the pervasive and most troublesome grass weed of irrigated wheat in rice-wheat cropping system in the northwestern Indo-Gangetic plains (Punia *et al.* 2017). Although *P. minor* infests several winter season crops but it has become pernicious in wheat due to its similar morphology and growth requirements. It emerges with the germinating wheat crop, competes for water and nutrients, and sig-nificantly reduces the grain yield due to its highly competitive ability.

Herbicides were largely accepted by the farmers to control this notorious weed. Isoproturon, a urea substituted herbicide, was the sole herbicide used for more than 15 years which provided very effective control of *P. minor* until the evolution of resistance in 1990s in Haryana and Punjab (Malik and Singh 1995). The indiscriminate and continuous use of isoproturon for more than a decade with an unbroken rice-wheat cropping pattern accentuated by poor application rates, spray techniques and timing, led to resistance in *P. minor*. An emergency recommendation of diclofop-methyl was made in 1992, which was withdrawn in two years due to the evolution of cross-resistance in *P. minor* without any history of previous use of this herbicide in India (Singh *et al.* 1999). Later, four alternative herbicides, *i.e.*, fenoxaprop, clodinafop, sulfosulfuron and tralkoxydim were recommended during 1997-98 for controlling *P. minor* (Chhokar and Malik 2002). In spite of their new mode of action as compared to isoproturon, these herbicides also met the fate similar to isoproturon after their continuous use for 8-10 years and complaints of their poor efficacy started appearing at farmers' fields (Singh *et al.* 2009).

Hence, new herbicide recommendations such as pinoxaden, mesosulfuron + iodosulfuron were introduced for the control of *P. minor* (Punia *et al.* 2008). However, the dreadful *P. minor* evolved biological defense against these new herbicides too. Some *P. minor* populations from Punjab and Haryana have been found to be insensitive to the application of pinoxaden without any prior history of exposure, indicating evolution of cross-resistance (Kaur *et al.* 2015). Similarly, few populations have been found to have very high GR_{50} value for mesosulfuron + iodosulfuron (Dhawan *et al.* 2012).

With the continued evolution of resistance to post-emergence (PoE) herbicides, the use of pre-emergence (PE) herbicides has emerged as an important approach to manage herbicide resistance. Herbicide-resistant weeds in wheat have been found susceptible to PRE herbicides such as pendimethalin, trifluralin, metribuzin, pyroxasulfone and flufenacet. However, if PE herbicides are used alone, these are not sufficient to achieve the objective of bringing down weed seed bank numbers but when used amongst a suite of tactics, these can be particularly effective. Some of the benefits of using PRE herbicides are that these offer an alternate mode of action to many PoE herbicides, reduce selection pressure on subsequent PoE herbicide applications and remove much of the early season weed competitive pressure on the crop (Singh 2015).

The objective of the present work was to investigate sequential applications of pre-emergence herbicides followed by post-emergence herbicides for the effective control of multiple herbicide-resistant *P. minor* in wheat.

MATERIALS AND METHODS

To evaluate the bio-efficacy of PE and PoE herbicides alone and in sequence against resistant *P. minor* in wheat, a field experiment was conducted in village Nangla district Fatehabad of Haryana, India (located at a latitude of 29º52' in the North and longitude of 75º45' in the East) in winter seasons of 2014-15 and 2015-16 in a grower's field infested with *P. minor* with a history of poor control with clodinafop and fenoxaprop. Nangla is characterized by semi-arid climate with hot and dry summers and extremely cold winters. The average annual rainfall varied from 350 to 400 mm. *P. minor* was the predominant weed species at the experimental site along with sparsely distributed broad-leaf weeds. The field had been under wheat in winter season with reliance on post-emergence herbicides mainly ACCase inhibitors for the control of *P. minor* for at least 8 years. The soil at the experimental site was determined as sandy loam in texture, slightly alkaline in reaction (pH 8.3) and normal in electrical conductivity (0.43 dS/m). The soil was found to be low in organic carbon (0.35%), nitrogen (210 kg/ha) and phosphorus (16 kg/ha). However, the soil was high in potassium (407 kg/ha). The wheat variety '*HD-2967*' was planted in a conventionally tilled seed bed using 100 kg seed per ha in rows spaced 18 cm apart. Wheat planting was done on 14^{th} November and 15^{th} November during 2014-15 and 2015-16, respectively. Standard agronomic practices of the state university were followed to raise the crop successfully.

The field experiment was arranged in a randomized complete block design with each treatment replicated thrice. The herbicide treatments evaluated to control resistant *P. minor* consisted of PE pendimethalin + metribuzin at two doses (1000 + 150 and 1500 + 150 g/ha), PoE mesosulfuron + iodosulfuron 14.4 g/ha, PoE sulfosulfuron + metsulfuron 32 g/ha, PoE pinoxaden + metsulfuron 64 g/ha applied alone and in sequences with PE pendimethalin 1.0 and 1.5 kg/ha, early post-emergence (EPoE) sulfosulfuron + metsulfuron 32 g/ha *fb* sulfosulfuron + metsulfuron 32 g/ha, PoE sulfosulfuron + clodinafop 25 + 60 g/ha and EPoE sulfosulfuron 25 g/ha *fb* PoE pinoxaden 60 g/ha. Weed free and weedy treatments were also included for comparison of efficacy. The PE herbicides were applied immediately after sowing in moist soil, EPoE herbicides were applied at 20 DAS and PoE herbicides were applied at 35 DAS with a knapsack sprayer fitted with a flood jet nozzle calibrated to deliver 500 l/ha spray volume for PE herbicides and a flat fan nozzle delivering 375 l/ha spray volume for EPoE and PoE herbicides.

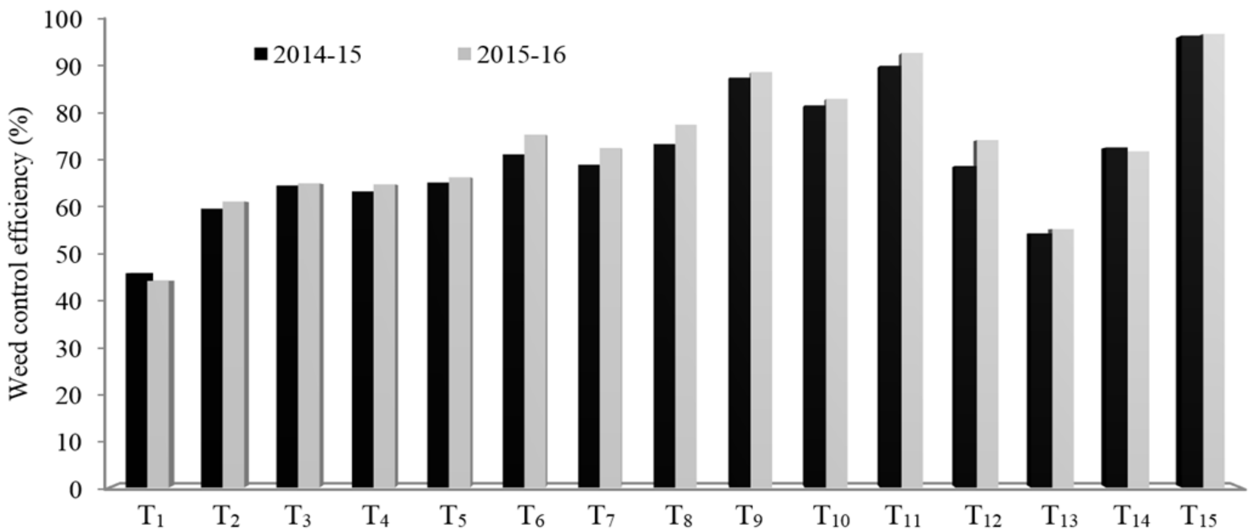
P. minor control was visually assessed at 30, 60, 90 DAS of wheat and at harvest stage of wheat on a scale of 0- to 100% with 0 percent meaning no control of *P. minor* and 100% meaning complete control of *P. minor*. The densities and dry weight of *P. minor* and broad-leaf weeds were also recorded on the same dates as mentioned for the visual control of *P. minor*. The weed samples from two randomly selected places in each plot were taken with the help of a quadrat (0.5 x 0.5 m). Each weed sample was separated as *P. minor* and broadleaf weeds. The number of plants of *P. minor* and broadleaf weeds in each sample was counted and is presented as number of plants/m^2. The plants of *P. minor* and broad-leaf weeds from each quadrat were first dried under the sun and then kept in oven at 65 ± 5^0C until a constant weight was achieved. Then dried weed samples were weighed and the weight taken was expressed as g/m^2. The weed control efficiency was computed as a percent reduction in weed density under different treatments in comparison to weedy at harvest. At physiological maturity, the crop was harvested and the grain yield was adjusted to 14% moisture content.

In order to see the significance of treatment's effect, the data were subjected to the statistical analysis by analysis of variance (ANOVA) technique. The significant treatment effect was judged with the help of F-test at 5 per cent level of significance. The data were analyzed separately for each year. The data on per cent visual weed control and biomass were arcsine and square root transformed, respectively before analysis.

RESULTS AND DISCUSSION

The weed flora of the experimental field constituted mainly of *Phalaris minor*. Broad-leaf weeds were present at comparatively lower densities and consisted mainly of *Chenopodium album*, *Rumex dentatus*, *Anagallis arvensis* and *Medicago denticulata*. The sequential herbicide mixture treatments had significant advantage over alone PE or PoE herbicide treatments in controlling *P. minor* indicated the importance of role of PE residual herbicides followed by PoE herbicides for *P. minor* control. The sequential application of PE pendimethalin 1.5 kg/ha *fb* PoE pinoxaden + metsulfuron 64 g/ha was the most effective treatment and provided 90% control of *P. minor* (**Figure 1**). Yadav *et al.* (2016) also indicated that the sequential application of pendimethalin with POE herbicides could improve weed control when PoE herbicides have a slightly poor efficacy. There was >90% reduction in dry weight of *P. minor* over weedy treatment with PE pendimethalin 1.5 kg/ha *fb* PoE pinoxaden + metsulfuron 64 g/ha (16.8-19.4 g/m^2) followed by 83-88% reduction compared to weedy plots with PE pendimethalin 1.5 kg/ha *fb* PoE mesosulfuron + iodosulfuron 14.4 g/ha (25.5-30.8 g/m^2) and sulfosulfuron + metsulfuron 32 g/ha (33.8-36.7 g/m^2). Sequential application of PE pendimethalin 1.0 kg/ha *fb* PoE herbicides improved weed control compared to alone PE or PoE herbicide treatments, however, their effect was less when compared to PRE pendimethalin 1.5 kg/ha *fb* PoE herbicides (**Table 1**).

Among sequential herbicide treatments, EPoE sulfosulfuron + metsulfuron 32 g/ha *fb* sulfosulfuron + metsulfuron 32 g/ha had more dry weight accumulation by *P minor* (57.2-64.7 g/m^2). PE pendimethalin + metribuzin 1000 + 150 g/ha recorded poor control of *P. minor* during both the seasons. The lack of mortality of *P. minor* plants at lower dose of



T_1- Pendimethalin + metribuzin, PE (1000 + 150 g/h); T_2 - Pendimethalin + metribuzin, PE (1500 + 150 g/ha); T_3 - Mesosulfuron + iodosulfuron, PoE (14.4 g/ha); T_4 - Sulfosulfuron + metsulfuron-methyl, PoE (32 g/ha); T_5 - Pinoxaden + metsulfuron-methyl, PoE (64 g/ha); T_6 - Pendimethalin *fb* mesosulfuron + iodosulfuron, PE/PoE (1000/14.4 g/ha); T_7 - Pendimethalin *fb* sulfosulfuron + metsulfuron-methyl, PE/PoE (1000/32 g/ha); T_8 - Pendimethalin *fb* pinoxaden + metsulfuron-methyl, PE/PoE (1000/64 g/ha); T_9 - pendimethalin *fb* mesosulfuron + iodosulfuron, PE/PoE (1500/14.4 g/ha); T_{10} - pendimethalin *fb* sulfosulfuron + metsulfuron-methyl, PE/PoE (1500/32 g/ha); T_{11} - pendimethalin *fb* pinoxaden + metsulfuron-methyl, PE/PoE (1500/64 g/ha); T_{12}- Sulfosulfuron + metsulfuron-methyl *fb* sulfosulfuron + metsulfuron-methyl, EPoE/PoE (32/32 g/ha); T_{13} -Sulfosulfuron + clodinafop, PoE (25+ 60 g/ha); T_{14} - Sulfosulfuron *fb* pinoxaden, EPoE/PoE (25/60 g/ha); T_{15} - Weed free;

PE, pre-emergence; PoE-post-emergence; EPoE, early post-emergence

Figure 1. Weed control efficiency (%) of different herbicide treatments for *P. minor* in wheat

pendimethalin could be attributed to the unavailability of lethal dose of herbicide to the weeds to cause mortality. The inefficacy of lower doses of pendimethalin has been found by earlier workers also. Yadav *et al*. (2016) found consistently ineffective control of *P. minor* with PE pendimethalin 1000 g/ha. Increasing the dose of pendimethalin in PE herbicide treatment significantly improved *P. minor* control and PE pendimethalin + metribuzin 1500 + 150 g/ha gave control of *P. minor* similar to alone PoE herbicides, however, these treatments were less effective compared to sequential herbicide treatments. Herbicide treatments with sulfosulfuron as mixture partner had reduced efficacy against *P. minor* compared to herbicide treatments with pinoxaden or mesosulfuron + iodosulfuron. This variation in weed control with different PoE herbicides could be due to variable resistance pattern observed in *P. minor* populations. *P. minor* populations have been reported to have high levels of heterogeneity which could be responsible for variable efficacy of different herbicides at different locations (Singh *et al*. 2004). Less control of *P. minor* in the present investigation with herbicide treatments having sulfosulfuron and clodinafop might be due to the evolution of resistance to these herbicides in *P. minor* population studied in the field.

Pre-emergence application of pendimethalin 1.5 kg/ha *fb* PoE mesosulfuron + iodosulfuron 14.4 g/ha caused maximum suppression of broad-leaf weeds (2.8-2.9 g/m^2) and brought >90% reduction in dry weight over weedy plots (30.2-32.5 g/m^2) (**Table 1**). Other sequential herbicide treatments produced similar reduction in dry weight accumulation by broadleaf weeds, however; EPoE sulfosulfuron 25 g/ha *fb* PoE pinoxaden 60 g/ha was the least effective treatment against broad-leaf weeds and had significantly more dry weight accumulation by broad-leaf weeds (11.1-12.6 g/m^2). This perhaps is due to the reason that EPoE sulfosulfuron 25 g/ha provided control of first cohorts of broad-leaf weeds and later emerging weeds were not controlled by pinoxaden which is a grass weed herbicide. Punia and Yadav (2010) also found pinoxaden as very effective against grassy weeds but did not control broad-leaf weeds. Dry weight accumulation by broad-leaf weeds was more in alone PE and alone PoE herbicide treatments compared to sequential herbicide treatments. Among herbicide treatments, highest dry weight by broad-leaf weeds was accumulated in plots treated with PE pendimethalin + metribuzin 1000 + 150 g/ha (16.1-17.6 g/m^2).

Better weed control with sequential herbicide treatments having herbicide mixtures is due to the enhanced period of weed control and weed spectrum. PRE pendimethalin eradicated first cohorts of weeds while the weak second and third cohorts were controlled by PoE herbicides. However, in alone PE herbicides the later emerging weeds continued to compete with the crop while in PoE alone treatments the primary weed cohorts get an early head start due to initial slow growth of crop and are then not

Table 1. Dry weight of weeds as influenced by different treatments

Treatment	Dose (g/ha)	Dry weight of *P. minor* (g/m^2)		Dry weight of BLW (g/m^2)	
		2014-15	2015-16	2014-15	2015-16
Pendimethalin + metribuzin, PE	1000 + 150	10.2 (103.7)	10.0 (99.1)	4.3 (17.6)	4.1 (16.1)
Pendimethalin + metribuzin, PE	1500 + 150	8.4 (69.6)	8.0 (63.0)	3.3 (10.1)	3.3 (9.8)
Mesosulfuron + iodosulfuron, PoE	14.4	8.3 (67.5)	7.7 (58.2)	2.6 (6.0)	2.7 (6.5)
Sulfosulfuron + metsulfuron-methyl, PoE	32	9.0 (80.7)	8.4 (69.6)	3.0 (8.1)	2.9 (7.7)
Pinoxaden + metsulfuron-methyl, PoE	64	8.4 (69.4)	7.8 (60.3)	3.2 (9.6)	3.3 (9.6)
Pendimethalin *fb* mesosulfuron + iodosulfuron, PE/PoE	1000/14.4	6.9 (47.0)	6.6 (43.3)	2.5 (5.2)	2.3 (4.3)
Pendimethalin *fb* sulfosulfuron + metsulfuron-methyl, PE/PoE	1000/32	7.9 (61.1)	7.1 (49.8)	2.6 (5.7)	2.4 (5.0)
Pendimethalin *fb* pinoxaden + metsulfuron-methyl, PE/PoE	1000/64	7.0 (47.9)	6.4 (39.4)	2.7 (6.0)	2.6 (5.8)
Pendimethalin *fb* mesosulfuron + iodosulfuron, PE/PoE	1500/14.4	5.6 (30.8)	5.1 (25.5)	2.0 (2.9)	1.9 (2.8)
Pendimethalin *fb* sulfosulfuron + metsulfuron-methyl, PE/PoE	1500/32	6.1 (36.7)	5.9 (33.8)	2.3 (4.2)	2.1 (3.6)
Pendimethalin *fb* pinoxaden + metsulfuron-methyl, PE/PoE	1500/64	4.5 (19.4)	4.2 (16.8)	2.4 (4.7)	2.2 (3.9)
Sulfosulfuron + metsulfuron-methyl *fb* sulfosulfuron + metsulfuron-methyl, EPoE/PoE	32/32	8.0 (64.7)	7.6 (57.2)	2.9 (7.3)	2.3 (4.4)
Sulfosulfuron + clodinafop, PoE	25+ 60	8.9 (78.2)	8.8 (77.1)	3.0 (8.0)	2.8 (7.0)
Sulfosulfuron *fb* pinoxaden, EPoE/PoE	25/60	7.6 (56.4)	7.4 (53.8)	3.7 (12.6)	3.5 (11.1)
Weed free	-	1.9 (2.7)	1.6 (1.5)	1.2 (0.5)	1.1 (0.3)
Weedy	-	14.8 (217.6)	14.4 (206.4)	5.6 (30.2)	5.8 (32.5)
LSD (p=0.05)		0.9	0.9	0.4	0.5

Original values in parentheses subjected to square root transformation before data analysis
PE, pre-emergence; PoE-post-emergence; EPoE, early post-emergence; DAS, days after so

effectively killed by PoE herbicides. Besides, the resistant plants of *P. minor* are not effectively controlled by alone PE or PoE herbicides (Singh 2015). Similarly, Yadav *et al.* (2016) found that the sequential application of pendimethalin 1000 g/ha or trifluralin 1000 g/ha just after sowing followed by clodinafop 60 g/ha or sulfosulfuron 25 g/ha at 35 DAS provided 90-100% control of *P. minor* along with broad-leaf weeds in wheat, thus resulted in improved grain yields when compared to clodinafop 60 g/ha or sulfosulfuron 25 g/ha alone. Abbas *et al.* (2016) attained effective control of fenoxaprop resistant as well susceptible *P. minor* with herbicide mixtures having 75% lethal dose of the herbicide without any adverse effect on wheat crop.

The high infestation of weeds in the weedy treatment robbed the crop of common resources from initial stages onwards. Hence, under stress the crop plants could not grow to their full potential, which ultimately reduced the grain yield to the extent of 43-45% (**Table 2**). In the present investigation, *P. minor* dominated the weed flora and severe reduction in wheat yield due to competition from *P. minor* has been reported earlier also (Brar and Walia 2008). The grain yield was significantly more in all the herbicide treatments as compared to weedy treatment. Further, the sequential herbicide mixture treatments were superior to alone PE or PoE herbicide mixture treatments and recorded higher grain yield. The sequential application of PE pendimethalin 1.5 kg/ha *fb* PoE pinoxaden + metsulfuron 64 g/ha recorded significant increase in grain yield (73-78%) over weedy treatment and produced grain yield (5.48-5.80 t/ha) comparable to weed free (5.65-5.88 t/ha) during both the crop growing seasons. PE pendimethalin 1.5 kg/ha *fb* mesosulfuron + iodosulfuron 14.4 g/ha (5.28-5.66 t/ha) being at par with PE pendimethalin 1.5 kg/ha *fb* sulfosulfuron + metsulfuron 32 g/ha (5.20-5.52 t/ha) produced wheat grain yield similar to PE pendimethalin 1.5 kg/ha *fb* pinoxaden + metsulfuron 64 g/ha. This could be ascribed to reduction in weed density and dry weight by the application of herbicides in sequence killing most of the weed cohorts which helped the crop to utilize nutrients, moisture, light and space more efficiently and thus produced more dry weight, more effective tillers, more grains per spike and test weight and hence increased grain yield. As compared to weed free check, the grain yield was reduced by 17-33% with the application of alone PE or PoE herbicide treatments and PE pendimethalin + metribuzin 1000 + 150 g/ha (3.76-4.04 t/ha) followed by sulfosulfuron + clodinafop 25 + 60 g/ha (4.40-4.61 t/ha) recorded the lowest grain yield among all herbicide treatments. This was perhaps because all the weed cohorts were not killed by alone PE and PoE herbicides and hence these weeds continue to grow with the crop plants competing with them for the natural resources and thus resulted in suppressed crop growth in terms of lower dry weight, lesser number of effective tillers, grains per spike and less bold grains and finally lower grain yields. Yadav *et al.* (2010) found superior or similar wheat grain yields with herbicide combinations compared to alone herbicides.

Table 2. Yield attributes and yield of wheat as influenced by different treatments

Treatment	Dose (g/ha)	Effective tillers/m^2		Grains/ spike		Test weight (g)		Grain yield (t/ha)	
		2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16
Pendimethalin + metribuzin, PE	1000 + 150	319	350	44	45	42.7	43.0	3.76	4.04
Pendimethalin + metribuzin, PE	1500 + 150	350	380	45	46	42.7	43.7	4.45	4.72
Mesosulfuron + iodosulfuron, PoE	14.4	366	396	47	47	41.5	43.0	4.52	4.75
Sulfosulfuron + metsulfuron-methyl, PoE	32	360	383	45	50	42.4	42.3	4.40	4.65
Pinoxaden + metsulfuron-methyl, PoE	64	373	395	48	50	42.5	43.3	4.67	4.90
Pendimethalin *fb* mesosulfuron + iodosulfuron, PE/PoE	1000/14.4	384	415	49	52	42.8	43.5	4.86	5.16
Pendimethalin *fb* sulfosulfuron + metsulfuron-methyl, PE/PoE	1000/32	380	409	50	51	43.0	43.0	4.71	5.05
Pendimethalin *fb* pinoxaden + metsulfuron-methyl, PE/PoE	1000/64	386	411	51	52	43.4	44.0	5.00	5.30
Pendimethalin *fb* mesosulfuron + iodosulfuron, PE/PoE	1500/14.4	417	461	54	54	43.3	44.6	5.28	5.66
Pendimethalin *fb* sulfosulfuron + metsulfuron-methyl, PE/PoE	1500/32	402	448	51	53	42.9	44.0	5.20	5.52
Pendimethalin *fb* pinoxaden + metsulfuron-methyl, PE/PoE	1500/64	439	472	55	54	45.0	45.0	5.48	5.80
Sulfosulfuron + metsulfuron-methyl *fb* sulfosulfuron + metsulfuron-methyl, EPoE/PoE	32/32	382	403	51	50	41.4	42.5	4.69	5.08
Sulfosulfuron + clodinafop, PoE	25+ 60	352	388	49	47	41.5	41.0	4.40	4.61
Sulfosulfuron *fb* pinoxaden, EPoE/PoE	25/60	388	391	53	52	43.5	43.8	4.72	5.15
Weed free	-	446	474	56	55	45.4	45.5	5.65	5.88
Weedy	-	272	300	31	32	35.3	38.3	3.08	3.34
LSD (p=0.05)		40	45	4	6	NS	NS	2.76	2.69

PE, pre-emergence; PoE-post-emergence; EPoE, early post-emergence

The findings of the present study clearly demonstrate that alone PE or PoE herbicide treatments are not effective against *P. minor*. However, the sequential application of PE followed by PoE herbicide with more than one mode of action could effectively control resistant *P. minor* in wheat by reducing the number of weeds to be killed by PoE herbicides and thus reducing the selection pressure on PoE herbicides. However, the continued evolution of resistance in *P. minor* due to the almost exclusive reliance on herbicides and also reduced discovery and commercialization of new herbicide chemistries over the last two decades, requires integration of herbicides with non-chemical weed control tactics so as to conserve herbicide resources for the future.

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